XVII. *Experiments and Observations to investigate the Nature of a Kind of Steel, manufactured at* Bombay, *and there called* Wootz: *with Remarks on the Properties and Composition of the different States of Iron. By* George Pearson, *M. D. F. R. S.*

Read June 11, 1795.

§ 1.

DOCTOR SCOTT, of Bombay, in a letter to the President, acquaints him that he has sent over specimens of a substance known by the name of wootz; which is considered to be a kind of steel, and is in high esteem among the Indians. Dr. SCOTT mentions several of its properties, and requests that an inquiry may be instituted to obtain further knowledge of its nature. This gentleman informs the President, that wootz "admits of a harder temper than any thing known in that "part of India; that it is employed for covering that part of "gun-locks which the flint strikes: that it is used for cutting iron on a lathe; for cutting stones; for chizzels; for "making files; for saws; and for every purpose where excessive hardness is necessary." Dr. SCOTT observes that this substance "cannot bear any thing beyond a very slight red heat, "which makes it work very tediously in the hands of smiths;" and that "it has a still greater inconvenience or defect, that "of not being capable of being welded with iron or steel; "to which therefore it is only joined by screws and other "contrivances." He likewise observes, that when wootz is "heated above a slight red heat, part of the mass seems to "run, and the whole is lost, as if it consisted of metals of different degrees of fusibility." We learn also from Dr. SCOTT's letter, that "the working with wootz is so difficult, that it is a "separate art from that of forging iron." It will be proper also to notice his observation, that "the magnetical power in "an imperfect degree can be communicated to this substance."

§ 2. *Mechanical and obvious Properties.*

The specimens of wootz were in the shape of a round cake, of about five inches in diameter, and one thick; each of which weighed somewhat more than two pounds. The cake had been cut almost quite through, so as to nearly divide it into two equal parts. It was externally of a dull black colour; the surface was smooth; the cut part was also smooth, and, excepting a few *pinny* places and small holes, the texture appeared to be uniform. It felt about as heavy as an equal bulk of iron or steel. It was tasteless and inodorous. No indentation could be made by blows with a heavy hammer; nor was it broken by blows which I think would have broken a like piece of our steel. Fire was elicited on collision with flint. Under the file I found wootz much harder than common bar steel not yet hardened, and than HUNTSMAN's cast steel not yet hardened. It seemed to possess the hardness of some kinds of crude iron, but did not effectually resist the file like highly tempered steel, and many sorts of crude iron: for although the teeth of the file were rapidly worn down and broken, the wootz was also reduced to the state of filings. The filed surface was of a bright bluish colour, shining like hardened steel; but some parts were brighter than others; and the most shining places seemed to be the hardest parts: hence perhaps the reason of the surface being uneven, and a little *pinny*. Notwithstanding this uneven and *pinny* appearance of the filed surface, a polish was produced, which was I think at least equal, if not superior, in brilliancy and smoothness to that of any steel I ever saw. The wootz filings were attracted by the magnet like common iron filings.

A cake of this substance being broken in the part nearly cut through, the fracture exhibited the grain and colour of rather open grained steel, but it was not nearly so open as I have constantly seen the grain of a bar of cement, or blister steel. The grain of wootz was most like that of blister steel which has been heated and hammered a little, and also like some kinds of refined crude iron.

The specific gravity of wootz, and several specimens of steel and iron, was found, by Mr. More and myself, to be as follows.

No. 1.	Wootz	7.181
No. 2.	Another specimen of wootz	7.403
No. 3.	Ditto forged	7.647
No. 4.	Another specimen, forged	7.503
No. 5.	Wootz which had been melted	7.200
No. 6.	Wootz which had been quenched while white hot	7.166
No. 7.	Bar steel from Oeregrund iron	7.313
No. 8.	Ditto hammered	7.735
No. 9.	German steel bar, said to be directly from the ore	7.500
No. 10.	Ditto quenched when white hot	7.370
No. 11.	Melted steel wire	7.500
No. 12.	Ditto, another parcel	7.460
No. 13.	Piece of hammered Oeregrund steel bar after quenching when white hot	7.555

No. 14.	Another parcel of ditto	7.570
No. 15.	Piece of same bar hammered, but not hardened by quenching	7.693
No. 16.	Piece of steel which had been often heated and cooled gradually	7.308
No. 17.	Huntsman's steel hammered	7.916
No. 18.	Ditto, another specimen	7.826
No. 19.	Ditto, another specimen	7.830
No. 20.	Ditto quenched when white hot	7.771
No. 21.	Ditto, another specimen so quenched	7.765
No. 22.	Piece of a file quenched while white hot to produce the appearance called, *open grain*	7.352
No. 23.	Another specimen of ditto	7.405
No. 24.	Piece of same file, but not so quenched	7.460
No. 25.	Another specimen of ditto	7.585
No. 26.	Piece of very hard steel	7.260
No. 27.	Hammered common steel	7.794
No. 28.	Another specimen of ditto, and hardened by quenching	7.676
No. 29.	Softest and toughest hammered iron; from Parkes, an iron merchant	7.716
No. 30.	Another specimen of ditto	7.700
No. 31.	Another parcel of ditto	7.780
No. 32.	Another specimen of ditto	7.787
No. 33.	Common hammered iron	7.600
No. 34.	Another specimen of ditto	7.450
No. 35.	Cast or brittle iron re-melted*	7.012

---

* Bergman states the specific gravities of steel and iron as follows: 1, steel 7,643.—2, Ditto 7,775.—3, Ditto 7,727.—4, Ditto 7,784.—5, Ditto indurated 7,693.—6, Wrought iron 7,798.—7, Ditto 7,829.

§ 3. *Effects of Fire.*

Until the substance was made red hot I could not scarcely make any impression with a hammer; nor could it be cut through by a chizzel, or wedge, till it was ignited to be of a pale red colour. It had then the peculiar smell of iron: it was then malleable, but was much more liable to be cracked and fractured by the hammer than common steel; or than, I think, even cast steel. Small and thin pieces are perhaps malleable at lower degrees of fire, but very slowly, and not without great care and management. That ingenious artist, Mr. Stodart, forged a piece of wootz, at the desire of the President, for a penknife, at the temperature of ignition in the dark. It received the requisite temper.* The edge was as fine, and cut as well as the best steel knife. Notwithstanding the difficulty and labour in forging, Mr. Stodart from this trial was of opinion, that wootz is superior for many purposes to any steel used in this country. He thought it would carry a finer, stronger, and more durable edge, and point. Hence it might be particularly valuable for lancets, and other chirurgical instruments.

Mr. More got a piece of wootz beat into a thin plate: in this state the texture did not seem to be uniform, but appeared to be of different degrees of hardness or kinds. A large piece also was forged into a thick bar for Sir Thomas Frankland.

(*a*) The pieces which had been cut in the ignited state abovementioned had smooth surfaces, with a few small cavities.

(*b*) The substance made white hot, by the forge, had the glassy smooth surface of iron, in what is termed the welding, or the welling* state. On striking it gently under the hammer, it was cracked in many places: and by a hard blow it was broken into a number of small pieces, as crude iron and cast steel are at this degree of ignition.

---

* "At the temperature of 450° of Fahrenheit's scale."—Mr. Stodart's letter to the President.

(*c*) The surfaces of the fractured pieces (§ 3. *b*) were black and ragged, or, as it is termed, had no grain. Two or three pieces indeed had yellow and reddish spots; but these were merely tinges from the fire, and disappeared on applying a few drops of muriatic acid.

(*d*) The pieces (§ 3. *c*) when cold were readily broken. Some of the fractures exhibited a bright silvery foliated grain, of seemingly an homogeneous substance, as frequently appears on breaking steel which has been quenched, when white hot, in cold water; and as also appears on breaking steel and crude iron which have been repeatedly ignited and cooled gradually; but many of the fractures of the small pieces were gray and close grained.

(*e*) A piece of the substance was ignited to whiteness, and then quenched in a large bulk of cold water. It was rendered much harder than before, so that a good file rubbed off very little. I cannot however from this experiment determine whether wootz is susceptible of a greater, or so great a degree of hardness as some kinds of steel used by the English artists.

(*f*) The piece (§ 3. *e*) was ignited in a close vessel, and let cool in the ashes of the fuel. It became much less hard, but I never could by annealing bring down the temper to the degree of any of our steels: on which account it is far more difficult to forge. The interior parts of a thick piece of wootz could not scarcely be softened at all by annealing.

---

* This term being from the German word *wellen.*

(*g*) A piece of the substance, about 500 grains in weight (wrapped in paper to afford carbon enough to prevent oxidation, without supersaturating the metal with carbon) was exposed in a close vessel for above an hour to a pretty considerable fire. On cooling, the substance was found to have retained its form, but it was of a slate-blue colour, and many round particles as large as pins heads adhered to its surface, as if matter had oozed out by melting. The degree of fire, indicated by WEDGWOOD's pyrometer, was 140°.

A piece of our steel, which had been a part of a file, was exposed in a similar manner, but to rather more fire. It retained its form, and its surface remained smooth.

A piece of crude, or cast iron, by exposure to this degree of fire, under the circumstances just mentioned, was fused: but in a temperature of about 120° its surface became covered with a number of smooth roundish masses, as if fusion had begun.

(*h*) 500 grains of wootz were exposed as in the former experiment, but to a fiercer fire, in my forge. The temperature was 148°; which is 23° more than Mr. WEDGWOOD states he could produce in a common smith's forge. My forge is moveable: the fuel is contained in a pan of cast iron lined with fire-bricks, as proposed by Mr. MORE: the bellows are only of the 22 inch size. In this fire the substance was melted with the loss of a few grains in weight. The surface was quite smooth. It broke under the hammer like cast steel. It received as fine a polish as that which had not been melted. Under a lens the polished surface appeared quite uniform and close, with a few pores at equal distances. The polished unmelted wootz had still fewer pores, and at unequal distances, but with several fissures. Its grain, in the opinion of Mr.

Stodart, was like that of cast steel of the best quality; consequently it was uniform and rather close. Its specific gravity, as already stated, was about 7,200.

500 grains of steel wire melted under the circumstances just mentioned. The mass which had been fused was fractured in the same manner, and had the same kind of grain, as wootz which had been melted.

I did not always succeed in melting wootz and steel, although the fire denoted by the pyrometer was of the same, or a higher temperature than that in which at other times they were melted. Nor is this result difficult to account for by those who consider the different temperatures in different parts of the same fire; even supposing the instrument to invariably indicate the real temperature.

(*i*) Equal weights, namely, 500 grains of wootz, steel wire, and gray pig iron, were exposed, for half an hour, in the same crucible well covered, to a pretty considerable fire. On cooling, the pig iron was found to have been fused, but the other two states of iron had retained their form. The pyrometer was contracted to near the 140th degree.

(*k*) I melted together 500 grains of steel wire and 50 grains of gray pig iron, in a close vessel, without any addition of carbon. The steel so alloyed was more brittle than cast steel. Its grain was coarser, and it had not the uniformity of texture and colour of melted wootz (§ 3. *h*); but had more resemblance to some of the fractures of the unmelted wootz (§ 3. *d*).

§ 4. *Effects of Fire and Oxygen Gaz conjointly.*

A piece of wootz ignited to whiteness, being exposed to a blast of air in the charcoal fire of the forge, emitted sparks like those of iron, and steel, in these circumstances. At the same time it melted in the state of oxide of iron.

§ 5. *Experiments with diluted Nitrous Acid.*

(*a*) 200 grains of the substance under examination were first digested, and afterwards boiled in three ounce measures of concentrated nitrous acid mixed with an equal bulk of water. A dissolution took place, with a discharge of nitrous gaz. The mixture, reduced by boiling to half its bulk, was diluted with water, and while boiling hot was filtrated through paper. Excepting a few grains of black matter, the whole mixture passed through the filtre. The filtrated liquor evaporated to dryness afforded matter, which after being kept red hot for two hours was a light spongy reddish substance that weighed 270 grains.

(*b*) 30 grains of the reddish substance (§ 5. *a*) digested in half an ounce of concentrated acetic acid, on filtration and evaporation to dryness yielded one grain and a half of gray matter, which was ascertained to be oxide of iron.

(*c*) The blackish matter left upon the filtre (§ 5. *a*) was repeatedly digested in diluted nitrous acid. The filtrated liquors on evaporation afforded at first a few grains of oxide of iron, and at last a very minute quantity.

(*d*) 60 grains of the reddish matter (§ 5. *a*) with a bit of sugar, were digested in diluted nitrous acid. The filtrated liquid on evaporation to dryness yielded a few grains of a brownish substance, which after many experiments, was found to be oxide of iron. Of these it will be satisfactory if I mention, that a little of the brownish substance fused with the fluxes by the flame and blowpipe, did not afford a reddish or purple glass from the exterior or white flame; nor a colourless one from the interior blue flame.

The experiments (§ 5. *a*—*d*) were also made on steel wire with the same result.

(*e*) A few drops of diluted nitrous acid were applied to a piece of polished wootz, steel, and iron. The parts of the wootz and steel so wetted became black, but the iron was made brown.

§ 6. *Experiments with diluted Sulphuric Acid.*

This acid liquor was made by mixing one measure of concentrated sulphuric acid with three of pure water.

Before I felt any degree of confidence in these experiments with respect to the carbon, and the proportions of hydrogen gaz from wootz and water, I repeated them often; but I here think it necessary to relate only one experiment.

200 grains of wootz, from the surface of which oxide, and any other extraneous matter, had been carefully rubbed off, were put into a retort with five ounce measures of diluted sulphuric acid. In the temperature of 55° of the room, in twenty-four hours, about a pint measure of gaz came over into a jar filled with, and standing over, lime-water; without any disturbance of its transparency, or diminution of the bulk of the gaz. The liquid in the retort became green, and a quantity of black wool-like sediment appeared upon the undissolved wootz.

On applying the lamp the dissolution went on rapidly, and black matter continued to be separated, and gaz to rise, till the whole of what seemed to be soluble in the menstruum disappeared. When about three-fourths of the matter were dissolved, a white sediment like the *siderite* of BERGMAN began to appear, and increased as the dissolution went on.

By standing, still more of this white sediment fell down, and green crystals, apparently those of sulfate of iron, formed a stratum which lay over the white matter. The black matter adhered to the sides of the retort, it appeared also upon the surface of the liquid, and some of it was deposited under the white sediment.

This experiment was made with steel wire, and the toughest iron wire.

The phænomena during the dissolution of steel were the same as those last related; except such as obviously arose from mechanical differences in the substances to be dissolved. In particular the quantity of insoluble black matter, of white sediment, and of green crystals, was apparently the same. But with respect to the phænomena of the dissolution of iron, there was one material difference between it and the dissolution of wootz and steel, namely, that the liquor was not turbid and black, but clear, with a very small quantity of black matter upon its surface. It is however proper to state, that seemingly the same kind and quantity of white sediment and green crystals were produced as from the dissolution of wootz and steel.

I think it of consequence also to notice, that the black matter appears in the greatest quantity when about half, or three-fourths of the matter is dissolved; but after this period, although gaz be separated in as great quantity as before, the black matter seems to diminish. Hence I was at first inclined to conclude with Mr. BERTHOLLET, that part of this black or carbonaceous matter was dissolved by the gaz, but I think I ſhall prove, that no such combination takes place; and I now consider it to be most probable, that the diminution arises from the dissolution of the last portions of adhering iron.

With respect to the quantities and nature of the gaz separated in this experiment:

I. The quantity of it from each hundred grains of wootz, on trials at different times, was found to be from 78 to 84 ounce measures: the mean quantity was therefore 81.

II. The gaz from each hundred grains of steel wire, after many trials, was found to be from 83 to 86 ounce measures: the mean quantity was therefore 84½.

III. The gaz from each hundred grains of bright iron wire, by many trials with the same and different parcels of wire, was found to be from 86 to 88 ounce measures: the mean quantity therefore was 87.

It is to be understood, that when the quantities of the different parcels of gaz were compared with one another they were measured at the same temperature, and under the same degree of pressure. It is likewise to be understood, that whenever the solutions of wootz, steel, and iron, were made at the same time, and under the same circumstances as far as known, there was uniformly a smaller bulk of gaz from wootz than from steel, and from steel than from iron.

The smell of the gaz from the above three substances was that of hydrogen gaz: but I thought that from wootz had a stronger and more offensive smell than from steel; and that from steel was more offensive than from iron.

I could perceive no difference in the kind of flame, and explosion, between these three parcels of hydrogen gaz: they burned in the same manner as common hydrogen gaz from sulphuric acid, iron, and water.

Portions of the above gazes mixed with oxygen gaz, from oxide of manganese, were burned in close vessels by the electric fire, over lime-water. I could perceive no difference in the combustion between the gazes from the above different substances, nor any difference in the gaz from the same substance at different stages of the dissolution. I did not perceive the lime-water to be at all disturbed in its transparency on my first trials; but in subsequent ones, on viewing it more attentively, and in a good light, it was perceived to be very slightly turbid. It was equally so with all the parcels of gaz.

To satisfy myself further, at the time I made these experiments I exploded the mixture of inflammable gaz, obtained by decompounding water with white hot charcoal of wood, with oxygen gaz; by which the lime-water was rendered quite milky. This inflammable gaz burnt very slowly, affording a deep blue lambent flame.

To determine the quantity, and ascertain the nature, of the undissolved black matter in this experiment, I poured the solutions, while boiling hot, upon filtres of three folds of paper, and freed the filtres from the adhering solutions by pouring boiling water upon them. The paper was stained black by the solutions of wootz and steel, as far as the liquid reached, but the paper was only stained black at the apex of the cone of the filtre by the solution of iron. The quantity of black matter on the filtres from the two former solutions was apparently six or eight times more than from the solution of iron: but it adhered too firmly, and was in too small a quantity, to determine the proportion accurately by weight. I estimated the quantity of the black matter to be one *per cent.* of the steel and wootz, and a proportionally smaller quantity from the iron. On account of the very black and turbid appearance during the dissolution of wootz and steel, I was much surprised by the smallness of the quantity of black matter on the filtres; nor could I by experiment find that any of it passed through the filtres with the solutions.

This black matter being sprinkled upon boiling nitre, a deflagration took place, and a large proportion of residue was found, and ascertained to be oxide of iron. The black matter was therefore a compound of iron and carbon, or, as some chemists term it, plumbago; and which in the new system is denominated a carburet of iron.

I estimate the quantity of carbon in wootz and steel to be nearly equal; and that quantity to be about one-third of a hundredth part, or $\frac{1}{300}$ of the weight of these two substances.

I am in the next place to give an account of the solutions just mentioned of wootz, steel, and iron. On standing, it has been observed, there was a deposition of white matter, and formation of green crystals in a liquid.

The liquid being decanted, was examined, and found to be sulfate of iron and superabundant diluted sulphuric acid.

The green crystals were obviously those of sulfate of iron.

The white matter I supposed was the *siderite* of BERGMAN; which is now believed to be phosphate of iron. I made many experiments to ascertain its nature, but it is only necessary to state; that it readily dissolved in hot water, and the solution afforded nothing but crystals of sulfate of iron. These crystals, by dissolving in a little water, and by boiling to leave behind water insufficient for crystallization, yielded on cooling a white sediment as before.

This white matter yielded colcothar, a red oxide of iron, by applying the flame with the blowpipe. The white matter therefore was not *siderite* but sulfate of iron, which could not crystallize on account of deficiency of water.

§ 7. *Experiments with Oxide of Wootz, Steel, and Iron.*

1200 grains of wootz dissolved by diluted sulphuric acid, and then precipitated from this acid by pot-ash, yielded greenish oxide; which on drying in a stove became a reddish-brown light powder, weighing 2700 grains; and by ignition it was reduced to 2000 grains.

300 grains of this oxide were made into a paste with linseed oil; which, being wrapped in paper, was put into a crucible and exposed for near an hour to a fierce fire in the wind furnace. On cooling, a cake of metal weighing 200 grains was obtained, which had the essential properties of steel. The pyrometer denoted 150° of fire.

The result was the same on treating oxide of steel, and of iron, in the same manner as wootz.

CONCLUSIONS.

Many of the properties of wootz, related in the preceding experiments and observations, are so generally known to be those of the metallic state of iron that, but for the sake of order, I should think it superfluous to refer to any of them particularly, to support the conclusion that wootz is at least principally iron. Wootz is proved to be iron by the obvious properties (§ 2.); by its filings being attracted by the magnet (§ 2.); by its specific gravity (§ 2.); by its affording nothing but sulfate of iron, hydrogen gaz, and a trifling residue, on solution in diluted sulphuric acid (§ 6.).

With regard to the particular state of iron, called wootz, I think I cannot explain its nature satisfactorily, without first relating the properties, and explaining the interior structure, of the principal different metallic states of iron. I imagine I shall be best able to execute this design by stating precisely the just meaning of the terms, which denote, commonly, the three principal metallic states of iron, namely, *wrought or forged iron, steel,* and *cast or raw iron.*

1. *Wrought* or *forged iron* I understand to be that which possesses the following properties.

a. It is malleable and ductile in every temperature; and the more readily the higher the temperature.

b. It is susceptible of but little induration (and if pure it is most probably susceptible of none at all) by immersing it, when ignited, in a cold medium; as in water, fat oil, mercury. Nor is it on the contrary susceptible of emollition by igniting, and letting the fire be separated from it very gradually.

c. It cannot be melted, without addition; but it may be rendered quite soft by fire, and in that soft state it is very tough and malleable.

d. It can easily be reduced to filings.

e. By being surrounded with carbon for a sufficient length of time, at a due temperature, it becomes steel.

f. It does not become black upon its surface, but equally brown, by being wetted with liquid muriatic and other acids.

g. By solution in sulphuric and other acids, it affords a residue of less than $\frac{1}{300}$ of its weight of carbon; and if it could be obtained quite pure, there is no good reason to suppose there would be any residue at all.

II. *Steel* I understand to be that which has the following properties:

a. It is already, or may be rendered, so hard by immersion, when ignited, in a cold medium, as to be unmalleable in the cold; to be brittle, and to perfectly resist the file; also to cut glass, and afford sparks of fire on collision with flint.

b. In its hardened state, it may be rendered softer in various degrees (so as to be malleable and ductile in the cold), by ignition and cooling very gradually.

c. It requires upwards of 130° of fire of the scale of WEDGWOOD's pyrometer to melt it.

d. Whether it has been hardened or not, it is malleable when ignited to certain degrees: but when ignited to be white, perfectly pure steel is scarcely malleable.

e. It becomes black on its polished surface by being wetted with acids.

f. Much thinner and more elastic plates can be made of it by hammering than of iron.

g. The specific gravity of steel which has been melted and hammered, is in general greater than that of forged iron.

h. With the aid of sulphuric acid it decompounds a smaller quantity of water than an equal weight of forged iron.

i. It decompounds water, in the cold, more slowly than forged iron.

k. By repeated ignition in a rather open vessel, and by hammering, it becomes wrought or forged iron.

l. It affords a residue of at least $\frac{1}{300}$ its weight of carbon on dissolution in diluted sulphuric acid.

m. It is more sonorous than forged iron.

n. On quenching in cold water, when ignited, it retains about $\frac{2}{3}$ of the extension produced by ignition; whereas wrought iron so treated returns to nearly its former magnitude.

III. By the term *Crude*, or *Raw Iron*, I understand that kind of iron which possesses the following properties:

a. It is scarcely malleable at any temperature.

b. It is commonly so hard as to resist totally, or very considerably, the file.

c. It is not susceptible of being hardened or softened, or but in a slight degree, by ignition and cooling.

d. It is very brittle, even after it has been attempted to be softened by ignition and cooling gradually.

e. It is fusible, in a close vessel, at about 130° of WEDGWOOD's pyrometer.

f. With sulphuric acid it generally decompounds a smaller quantity of water than an equal weight of steel.

g. It decompounds water in the cold more slowly than wrought iron.

h. It unites to oxygen of oxygen gaz as slowly, or more slowly than even steel.

i. By solution in sulphuric and other acids, it leaves a residue not only of carbon, but of earth; which exceed the quantity of residue from an equal weight of steel.

k. It is perhaps more sonorous than steel.

With respect to interior structure:

I. *Wrought iron* is to be considered as a simple or undecompounded body, but it has not been hitherto manufactured quite free from carbon; which is to be reckoned an impurity.

The least impure iron, as indicated by properties, is that which possesses the greatest softness, toughness, and strength; but if it be soft, independent of combination, it will of course be of the toughest and strongest quality. To denominate it from properties, I would call it *soft malleable iron:* and from internal structure, it should be called *pure iron*, or *iron.*

The ore from the deep mines of Dannemora, produces the purest iron. It is in England called *Oeregrund iron.*[*] It is almost the only iron manufactured which by cementation affords what our artists reckon good steel.

II. *Steel* has composition. It is a compound of iron and carbon, the proportions of which have not been accurately determined, but may be estimated to be one of carbon and 300 of iron. I would call this state of iron from external properties, *hard malleable iron:* and from interior structure and composition it may be called, as in the new system, *carburet of iron.*

Steel of the best imaginable kind is that which has not yet been manufactured: for it is that which has the most extensive range of degrees of hardness, or temper; the greatest strength, malleability, ductility, and elasticity; which has the greatest compactness or specific gravity, and which takes the finest polish; and lastly, which possesses these qualities equally in every part. Steel made by cementation, of the best quality, which has been melted, approximates the nearest to this kind of steel. Its greatest defect is want of malleability.

---

[*] *Oeregrund* is not the name of the country in which the ore of this iron is gotten; or of the place where it is manufactured; but it is the name of a sea-port town, from which the iron of Dannemora was formerly exported.

III. *Crude* or *raw iron* is a mixture, and has composition. It consists of pure iron united, and mixed with other substances so as to be hard unmalleable iron: but the substances with which it is almost always mixed and united are three, *viz.* oxygen, carbon, and earth. I would term this state of iron, on account of external properties, *hard unmalleable iron*; and on account of structure, *impure iron*.

In this statement of the interior structure of the different states of iron I have not thought it necessary to reckon the impalpable fluids, which they contain in perhaps different proportions; *viz.* light, caloric, electric, and magnetic fluids: for I believe their chemical agency has not been ascertained.

Iron may also contain a much greater quantity of carbon than has been above stated to be a constituent part of steel; and this state of iron is hard, unmalleable, and is not uniform in its texture. It may be called, according to the new nomenclature, *hyper-carburet of iron*. It is liable to be produced by cementing iron in a very high temperature for a very long time, with a large quantity of carbon; and it is also produced by melting iron, or steel, with carbon.

There are innumerable varieties of the first explained state of iron, viz. *wrought iron*. Some of these are familiarly known and distinguished by names among artists. Different quantities of carbon, which is here an impurity, are the occasion of these varieties; but as the carbon is not in sufficient quantity to diminish the toughness, softness, and malleability, to such a degree as to produce the obvious qualities of steel, such varieties are reckoned to be those of wrought iron. The carbon may however be in such proportion as to produce a state of iron, which in some degree possesses the properties both of steel, and wrought iron; or which possesses partly the properties of steel, and partly the properties of wrought iron. It is quite arbitrary to call such kinds of iron, steel or wrought iron.

There are also innumerable varieties of the second state of iron explained, *viz. steel.* Some of these are known and distinguished by artists. A greater, or smaller, proportion of carbon, than the quantity requisite to saturate the iron, is the cause of these varieties: which are reckoned varieties of steel, because they possess in certain degrees the distinguishing properties of steel.

Besides these varieties of iron and steel depending upon carbon, there are other varieties from extraneous substances of a different nature. These are most frequently oxide of iron, or oxygen, and silica; especially in steel from the ore. The presence of phosphoric acid has been shown to be the occasion of the variety of iron, named *cold short*; which is brittle when cold, but not when ignited. And there is another variety called *red short*, which is malleable when cold, but brittle when ignited; the cause of which is supposed to be arsenic.

Iron and steel may contain an extraneous substance, and yet possess the properties of good, or even the best kinds of these metals: for this is the case when they contain manganese; as the fine experiments of Professor GADOLIN, made under the direction of BERGMAN, have demonstrated.

There are states of iron which are mechanical mixtures of steel and wrought iron. This is more or less always the case with *bar steel,* made by cementation. If the bar be thick the interior part will be mere iron.

Lastly. There are different sorts of steel and wrought iron, from the difference of mechanical arrangement of their parts. So the specific gravity of steel by cementation may be increased by fusion, or hammering, and its grain altered. I have been told, that it may be hammered in the cold till it is so brittle that a slight stroke will break a thick bar. By quenching close-grained hammered steel in cold water, when ignited to whiteness, its specific gravity is diminished, its grain is opened, and it is rendered much harder.

These distinctions will perhaps serve to explain the nature of many varieties of the different states of iron, differently named by artizans, namely, *pig-iron; charcoal,* and *coal pig,* or *sow iron; blue, gray, white cast iron;—soft iron; tough iron; brittle iron; hard iron;—ore steel; cement steel; blister steel; soft steel; hard steel; hammered steel; cast steel; burnt steel; over cemented steel.*

I shall next endeavour to show to which of the above states of iron the wootz is to be referred, or to which of them it most approximates.

It appears that wootz is not at all malleable when cold; and when ignited it is difficultly forged and only in certain degrees of fire. It can be tempered and distempered, but not to a considerable extent of degrees (§ 3. *f, g*). The range of degrees of fire at which it is forged is of less extent (§ 3. and § 3. *c*) than the degrees at which it can be tempered, (§ 3. and § 3. *f, g*). It vies with the finest steel in its polish. Its specific gravity, which is less than that of hammered iron, is very little diminished by ignition and cooling rapidly (§ 2. No. 6.). It melts, but at a higher temperature than crude iron (§ 3. *i*, *k*). It is not easily reduced into filings, even after annealing (§ 3. *g*). Its polished surface grows black by being wetted with acid (§ 5. *e*). It is not so brittle as raw iron, nor even as steel (§ 2.). On solution in sulphuric acid and water, it affords about the same quantity of carbon, and rather less hydrogen gaz than steel (§ 6.).

From these and other properties related in the preceding experiments and observations, it is evident that wootz approaches nearer to the state of steel than of raw iron; although it possesses some properties of this last substance.

With regard to the kind of steel to which wootz is to be referred; it is not of that sort in which there is either an excess or deficiency of carbon (p. 341, l. 15, *et seq.*); but it must contain something besides carbon and iron, otherwise it would be common steel. It appears that the solution in nitrous (§ 5.) and diluted sulphuric acids (§ 6.) contained only oxide of iron, and the residue of carbonaceous matter, as in common steel. Hence it is obvious to suspect that wootz contains oxygen, either equally united with every part of the mass, or united with a portion of iron to compose oxide; which is diffused throughout the mass. That this is really the ingredient in wootz which distinguishes it from steel, seems to be proved, or at least consists with its properties. For it accounts for the smaller quantity of hydrogen gaz than was afforded by common steel (§ 6.): it accounts for the partial fusion (§ 3. *h*): it accounts for the great hardness even on reducing its temper (§ 3. *g*); for its little malleability (§ 3.); perhaps it is the reason of the fine edge and polish

(§ 2, § 3.). The experiments (§ 3. *g*, *h*) confirm this conclusion. The oxide is not perhaps equally diffused, hence the wootz is not quite uniform in its texture and hardness, until it has been remelted (§ 3. *i*). The brittleness of wootz when white hot (§ 3. *g*) is a property of cast steel; and shows that it contains no veins or particles of wrought iron, and also that it has been melted. Common steel, which is all made by cementation, is very malleable, when white hot, only perhaps because it contains iron which has escaped combination with carbon.

The proportion of oxygen in wootz must be very small, otherwise it would not possess so much strength, and break with so much difficulty (§ 2.), and much more oxide would have melted out (§ 3. *h*). This oozing out of matter is analogous to that which appears on refining raw iron.

Although no account is given by Dr. Scott of the process for making wootz, we may without much risk conclude that it is made directly from the ore; and consequently that it has never been in the state of wrought iron. For the cake is evidently a mass which has been fused (§ 2.), and the grain (§ 2.) of the fracture is what I have never seen in cement steel before it is hammered or melted. This opinion consists with the composition of wootz, for it is obvious, that a small portion of oxide of iron might escape metallization, and be melted with the rest of the matter. The cakes appear to have been cut almost quite through while white hot (§ 2.), at the place where wootz is manufactured; and as it is not probable that it is then plunged in cold water, the great hardness of the pieces imported, above that of our steel, must be imputed to its containing oxide, and consequently oxygen.

The particular uses to which wootz may be applied may be inferred from the preceding account of its properties and composition: they will also be discovered by an extensive trial of it in the innumerable arts which require iron.